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How rebound effects of efficiency improvement and price jump of energy influence energy consumption?

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ABSTRACT

Energy efficiency improvement is usually regarded as an effective way to decrease energy consumption and to fight climate change, but it also booms energy consumption through rebound effects. But the improvement of energy efficiency also has rebound effects, which increases energy consumption and emission. So this paper arms to capture the rebound effects of efficiency improvement by considering zero-cost breakthrough of energy efficiency and price jump of energy purchase. First, energy efficiency improvement, measured by zero-cost breakthrough of energy efficiency, stimulates energy consumption, but it may reduce the total emission. Second, both the direct and indirect rebound effects of energy efficiency improvement on energy consumption and environment are captured. Interestingly, jumping energy price decreases both the direct and indirect rebound effect. Finally, the result of the paper shows that restriction of individuals' entry or competition restriction moderates the rebound effects of energy efficiency improvement.

1. Introduction

Energy efficiency is defined to the ratio between the useful output and input of an energy conversion process and higher energy efficiency means lower emission. Energy efficiency improvement, by energy subsidy or innovation subsidy, is usually regarded as an effective way to decrease energy consumption and to fight climate change. And energy efficiency promotion is seen to be a vertical pathway for reducing the pressure on energy and the environment. So many countries, such as China, the United States and France, are trying their best to improve their energy efficiency. But energy efficiency promotion also leads to rebound effects. Rebound effects means the improvement of energy efficiency will increase energy consumption (Galvin and Sunikka-Blank (2016), which can even make energy policies fail. For example, more vehicles will be drove to the highway after gasoline efficiency improvement and more gasoline will be used because energy efficiency promotion reduces the costs. Governors should take rebound effects into consideration when they decide to implement efficiency improvement policies. These phenomena we mentioned above make rebound effects of energy efficiency a major issue in environmental protection.

The major purpose of the paper is to illustrate the rebound effects of energy efficiency improvement on energy consumption in theory. The improvement of energy efficiency in this paper is measured by zero-cost breakthrough, which means firm achieves one time energy efficiency promotion without any cost increase. Please notice that industrial economics theory shows that competition and price fluctuation have significant influence to products purchase, while energy part is such an industry with high competition and price volatility. So this paper also investigates the impacts of competition intensity and price fluctuation on the effects of energy efficiency improvement. Competition intensity is evaluated by total firms' number and price fluctuation is measured by price jump. Price jump means a sharp price arising.

Cournot competition, with inherent advantage in revealing quantity competition is a popular model in microeconomic theory and game theory. Under Cournot competition, firms will make quantity decision by take rivals' strategies into account simultaneously. At the same time, total number of firms is used to capture market competition intensity, so we establish a Cournot competition model about the rebound effect of energy efficiency promotion on energy consumption under multiple-oligopoly condition. Furthermore, we also isolate indirect effect of energy efficiency

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Nomenclatures

u_0	Reservation utility
θ	Preference level of possible consumer
p	Price of final products
τ	Energy price
$\tilde{\tau}$	Jumped energy price
ε	Energy efficiency
$\tilde{\varepsilon}$	Improved energy efficiency
EM	Emission
TEM	Total emission
c	Marginal cost of final products
e	Energy consumption
N	Number of consumers
K	Number of firms
q_i	Outputs of the firm
Q	Total outputs
Q_e	Total energy demand
π_i	Firms' profits
A	Market capacity
B	Demand elasticity

from direct effect. But both direct and indirect effects are different from other studies. Direct effect means the increase of energy consumption for each consumer, while indirect effect of energy efficiency improvement results in market expansion.[1] By game theory model, we find that competition of final products amplifies the energy efficiency rebound effects of energy consumption and total emission. Besides, influences of zero-cost breakthrough and price jump are also investigated in the study.

The novel contribution of this article is to develop the impacts of competition on the energy efficiency rebound effects in theory and bring the influence of price fluctuation on rebound effects of energy efficiency improvement to light. To our best knowledge, no prior studies involve those issues we mentioned above to study rebound effects in energy consumption. The industrial organization theory is employed to analyze energy efficiency rebound effects under multiple-oligopoly competition. In application, this article supports entry regulation about industry depended on energy to maintain a sustainable development because more firms mean intenser competition while fiercer competition leads to more energy purchase.

The rest of this article is organized as follows: Literature review is outlined in Section 2. Basic model is established in Section 3. The benchmark model is analyzed in Section 4 and some basic results are achieved. Effects of zero-cost breakthrough are discussed in Section 5. Both fixed energy price and changed energy price are addressed. Conclusions are remarked in the final section.

2. Literature review

It can learn that, energy efficiency attracted more and more attention all over the world after 1970s oil crisis, by reviewing the existing research literature (Nie et al., 2016a, b, Chen et al., 2018a, b), such as USA (Orea et al., 2015), Chile (Norero and Sauma, 2012), China (Nie and Yang, 2016; Chen and Nie, 2016; Sun and Nie, 2015; Jiang et al., 2016; Wang et al., 2017) and so on. As known, energy efficiency promotion has two-fold effects: On one hand, consumers benefit from energy efficiency promotion. On the other hand, energy-consumption-based products resulting in energy efficiency promotion yield more energy consumption, which is a type of rebound effect (Gillingham et al., 2016; Berkhout et al., 2000). Galvin and Sunikka-Blank (2016) investigated the influence of the rebound effects. They found that rebound effects, as defined in econometrics literature, indicate proportionate reductions in energy consumption and mask high levels of absolute consumption.

Berkhout et al. (2000) defined the rebound effects of energy efficiency as the lost part of energy conservation from energy efficiency promotion. Concerning the rebound effects of energy efficiency, research mainly focuses on rebound effects of some countries, economics and energy policies (Gillingham et al., 2013; Nie et al., 2016; Yang and Nie, 2016a; Yang et al. 2016; Nie et al., 2016b, Nie et al., 2018a, b). Rebound effects of energy efficiency differ in different regions and industries, and it is important to access rebound effects of energy efficiency (Watts et al., 2005). Li and Lin (2017) examined rebound effects of residential building industry in China. Further studies about rebound effects in China were launched by Fan et al. (2016) and Wang et al. (2016), Norero and Sauma (2012) identified the energy efficiency rebound effects of Chile. Gillingham et al. (2015) testified the rebound effects of Pennsylvania State in USA. Moreover, Min et al. (2015) identified the regional difference of the rebound effects of energy efficiency in USA. In addition, Fujimi et al. (2016) checked the energy efficiency rebound effects in Japan. Lin and Tian (2017) estimated the possible energy conservation potential in China by considering energy rebound effect. Almost all those researchers agree that energy efficiency rebound effects exist for all countries or regions.

Effect efficiency promotion can lead to both direct and indirect rebound effects. Freire-Gonzalez (2017a) identified direct and indirect rebound effects of energy efficiency and tried new way to measure these two effects. He illustrated that most of the prior research focus on the indirect effects. For example, Hache et al. (2017), Freire-Gonzalez (2017b) focused their study on French residential housing market and highlighted the indirect influence of rebound effect of energy efficiency. But Zhang and Peng (2017) investigated direct rebound effect of residential electricity consumption in China. The meanings of direct and indirect rebound effects in this study are different from those studies mentioned above and we define them from industrial economics perspective.

Also, some special industries are focused by researchers in recent years. Hymel and Small (2015) examined energy efficiency rebound effects of automobile industry. Galvin (2016) also pointed out the rebound effects of electric and internal combustion engine car industry. Rebound effects are different for different industries. Llorca and Jamasb (2017) investigated the rebound effect of energy efficiency in European road freight transportation and issued that energy efficiency has become a primary energy policy goal in Europe. Georges et al. (2017) studied rebound effect in direct control service by residential heat pump. Li et al. (2017) captured the energy rebound effects across China's industrial sectors and found that rebound effects in China are very strong.

Although existed literature shows the difference of energy efficiency rebound effects for regions and industries, rare research about the relationship between competition degree of products and energy efficiency rebound effects is launched. Actually, competition has significant effects on the energy efficiency rebound effects. Energy efficiency promotion stimulates product demand. The faster products demand grows, the more the energy consumption increases. There was no doubting that a considerable rise in energy consumption increases the emission. The rebound effects of energy efficiency promotion are difficult to the environmental sustainable development. Looking for strategies that can

[1] We define the direct and indirect rebound effects of energy efficiency from industrial economics perspective.

relieve the rebound effects has become the most important.

3. Model

Here we establish a Cournot competition model about the rebound effect of energy efficiency promotion under multiple-oligopoly. Cournot competition is used to model quantity competition and multiple-oligopoly is employed to capture competition intensity. Assume that there are K firms in this industry with final products heavily depended on energy. Consumers purchasing these products need energy to improve the utility. This article neglects energy consumption in production but highlights energy consumption in the use of the final products. For example, consumers buying cars require energy to operate their cars. Energy demand in driving cars is much more than that in production. Both consumers and producers are addressed.

Consumers Assume that there are N possible consumers in this market. Given the price of final products p and energy efficiency ε, the utility function of buying a unit product is

$$u(\theta,\varepsilon,p)=\theta u_0-p+(\varepsilon-\tau)e-\frac{1}{2}e^2, \tag{1}$$

where τ is the energy price, e is the energy consumption and u_0 is the reservation utility. $\theta\in[0,1]$ stands for preference level of possible consumer, which observes some distribution. Here, energy efficiency ε represents the utility of each unit of energy to consumers, so we assume $0<\tau<\varepsilon<1$ to simplify the model. In this article, we always assume that the random variable $\theta\in[0,1]$ satisfies normal distribution with dense function $f(\theta)=1$. According to function (1), high energy efficiency promotes consumers' utility, and the term $\frac{1}{2}e^2$ manifests costs of consumers in using this product to consume energy e. The term εe is the utility of consumers from energy consumption, which is increased with energy efficiency. τe is the cost to buy energy.

We assume that the emission is $EM(\varepsilon,e)=(1-\varepsilon)e$, which observes the law of entropy about energy. Namely, high energy efficiency means low emission or the emission is reduced with the improvement of energy efficiency. Moreover, if a consumer does not buy this product, his or her utility is equal to zero. A consumer with state θ buys a unit product if and only if $u(\theta,\varepsilon,p)\geq 0$. Denote the total energy demand in this industry to be $Q_e(p,\varepsilon)$. For each (possible) consumer, the optimal energy demand is[2]

$$e^*=\varepsilon-\tau. \tag{2}$$

The emission of each consumer is

$$EM=(1-\varepsilon)(\varepsilon-\tau). \tag{3}$$

According to equation (3), the relationship between emission and energy efficiency is inversed U-shape and the emission reaches the highest under $\varepsilon=\frac{1+\tau}{2}$. This means that the improvement of technology first increases $\left(\varepsilon\leq\frac{1+\tau}{2}\right)$ the emission of each consumer and then decreases $\left(\varepsilon\geq\frac{1+\tau}{2}\right)$ it.

However, when $u(\theta,\varepsilon,p)\geq 0$, the consumer will buy the final product. Denote$\tilde{\theta}=\frac{p-\frac{1}{2}(\varepsilon-\tau)^2}{u_0}$satisfied $u(\tilde{\theta},\varepsilon,p)=0$, and the parameter $\theta\in[\tilde{\theta},1]$ satisfies normal distribution with dense function $f(\theta)=1$. Therefore, the expected value of the number of consumers is $N(1-\tilde{\theta})$ and the total demand of energy in this industry is given by the following formulation.

$$Q_e=N\left(1-\tilde{\theta}\right)e^*=N\left[1-\frac{p-\frac{1}{2}(\varepsilon-\tau)^2}{u_0}\right](\varepsilon-\tau). \tag{4}$$

By equation (4), $\frac{\partial Q_e}{\partial\varepsilon}\geq 0$means high energy efficiency improves the demand of energy, while $\frac{\partial Q_e}{\partial\tau}\leq 0$indicates high energy price reduces the demand. The total emission (TEM) is

$$TEM=EM\bullet N\left(1-\tilde{\theta}\right)=N\left[1-\frac{p-\frac{1}{2}(\varepsilon-\tau)^2}{u_0}\right](\varepsilon-\tau)(1-\varepsilon). \tag{5}$$

According to equation (5), we also know that technology first increases, and then decreases the total emission.

Producers Here we further address firms and firms' compete in quantity. Assume that the final outputs of firm i are q_i and outputs of the firms are symmetric. The total outputs are $Q=q_1+q_2+\cdots+q_K$. Based on equation (4), the linear inverse demand is employed as follows[3]

$$p=A-BQ, \tag{6}$$

where $A=u_0+\frac{1}{2}(\varepsilon-\tau)^2>0$ and $B=\frac{u_0}{N(\varepsilon-\tau)}$ are two parameters depending on energy efficiency and energy price. A represents market capacity, and increases with energy efficiency. B is demand elasticity, and decreases with energy efficiency.

For $i\in\{1,2,\cdots,K\}$, firms' profits are stated as follows.

$$\pi_i=pq_i-cq_i, \tag{7}$$

where $c>0$ is a constant, and represents the marginal cost of final products. In function (7), the term pq_i manifests the revenues and cq_i is the costs incurred by production. Compared with existed literature about the rebound effects, we focus on energy consumption and emission.

4. Main results of benchmark model

The above model is analyzed in this section under benchmark model or basic Cournot model. Benchmark model means no zero-cost breakthrough of energy efficiency and no price fluctuation in energy industry. By virtue of functions (5), (6) and (7), we know that function (7) is concave in q_i and the unique solution exists, which is determined by the first-order optimal conditions. By direct calculation, the equilibrium supply is

$$q_1^*=q_2^*=\cdots=q_K^*=\frac{A-c}{B(K+1)}. \tag{8}$$

Market clearing conditions imply that the demand is exactly equal to supply, so the total demand is $Q=\frac{K(A-c)}{B(K+1)}$. The corresponding price is

$$p^{*1}=A-\frac{K(A-c)}{K+1}=\frac{A+Kc}{K+1}. \tag{9}$$

The total energy demand is

[2] According to (1), the first derivative of utility function is $\frac{\partial u}{\partial e}=\varepsilon-\tau-e$, so the optimal energy demand $e^*=\varepsilon-\tau$.

[3] This is a general demand function in economics (*e.g.* Sacco, Schmutzler, 2011; Chen et al., 2017; Nie et al., 2018a, b; Chen et al., 2018a, b).

$$Q_e^{*1} = N\left(1-\theta^{*1}\right)e^* = N\left[1-\frac{p^{*1}-\frac{1}{2}(\varepsilon-\tau)^2}{u_0}\right](\varepsilon-\tau). \tag{10}$$

The total emission (TEM) in this industry is

$$\begin{aligned} TEM^{*1} &= EM \bullet N\left(1-\theta^{*1}\right) \\ &= N\left[1-\frac{\frac{A+Kc}{K+1}-\frac{1}{2}(\varepsilon-\tau)^2}{u_0}\right](\varepsilon-\tau)(1-\varepsilon). \end{aligned} \tag{11}$$

According to equations (8) and (9), we obtain the following conclusion.

Proposition 1. (*a*) *Improving energy efficiency* (*or reducing energy price*) *advances both the total supply and price of the final products.* (*b*) *Competition promotes outputs but reduces the price of the final products.*

Proof. See in Appendix. ■

Promoting energy efficiency improves the utility of a unit product $u(\theta,\varepsilon,p)$and the total demand (or the supply) is also promoted correspondingly. Moreover, the promoting of energy efficiency increases market size. Summarized these two effects, we know that the improvement of energy efficiency also promotes the price of the final products.

About competitive effects, fiercer competition yields more outputs and lowers the price of the final products, which is a common conclusion in the microeconomics and the industrial organization theory (Nie and Chen, 2012; Chen et al., 2015; Yang and Nie, 2016; Nie et al., 2017; Nie et al., 2018a, c). And we ignore the details of this issue here.

Here, we further address the environmental effects of promoting energy efficiency. Equation (11) can be rewritten as $TEM^{*1} = N\left[\frac{Ku_0-Kc+\frac{K}{2}(\varepsilon-\tau)^2}{u_0(K+1)}\right](\varepsilon-\tau)(1-\varepsilon)$. Based on equations (9) and (11), we have the following conclusion.

Proposition 2. *Higher energy price yields lower total emission, while Competition increases the total emission.*

Proof. See in Appendix. ■

High energy price increases the costs and deters the consumption of energy. Thus, high energy price yields low total emission. Based on Proposition 1, fiercer competition yields more outputs and more total emission. Therefore, high energy price yields low total emission but competition increases it.

In this section, benchmark model is discussed. Effects of energy efficiency, energy price and competition on outputs, price of the final product and emission are all captured. Benchmark model is used to capture the general conclusions under Cournot competition. But just as we illustrate above that energy efficiency improvement and price fluctuation have critical influence on energy, so in next section, a zero cost breakthrough about energy efficiency both under No-price jump and price jump conditions are introduced.

5. Conclusions of rebound effects under zero-cost breakthrough

5.1. No-price jump of energy

Here, a zero-cost breakthrough about energy efficiency is introduced. After the zero-cost breakthrough, energy efficiency becomes $\tilde{\varepsilon}$, where $\varepsilon < \tilde{\varepsilon} < 1$. Similar to those in Section 4, we have the following equilibrium. For each (possible) consumer, the optimal energy demand is

$$e^{*,2} = \tilde{\varepsilon}-\tau. \tag{12}$$

The corresponding emission of each consumer is

$$EM^{*,2} = (1-\tilde{\varepsilon})(\tilde{\varepsilon}-\tau). \tag{13}$$

Denote $\tilde{A} = u_0 + \frac{1}{2}(\tilde{\varepsilon}-\tau)^2 > 0$ and $\tilde{B} = \frac{u_0}{N(\tilde{\varepsilon}-\tau)}$. The total demand (or supply) of final products is $\tilde{Q} = \frac{K(\tilde{A}-c)}{\tilde{B}(K+1)}$. The corresponding price of final products is

$$p^{*,2} = \frac{\tilde{A}+Kc}{K+1}. \tag{14}$$

The total energy demand is

$$Q_e^{*2} = N\left(1-\theta^{*2}\right)e^{*2} = N\left[1-\frac{p^{*2}-\frac{1}{2}(\tilde{\varepsilon}-\tau)^2}{u_0}\right](\tilde{\varepsilon}-\tau). \tag{15}$$

The total emission (TEM) in this industry is

$$\begin{aligned} TEM^{*,2} &= EM^{*,2} \bullet N\left(1-\theta^{*2}\right) \\ &= N\left[1-\frac{\frac{\tilde{A}+Kc}{K+1}-\frac{1}{2}(\tilde{\varepsilon}-\tau)^2}{u_0}\right](\tilde{\varepsilon}-\tau)(1-\tilde{\varepsilon}). \end{aligned} \tag{16}$$

We define the direct rebound effects of energy efficiency improvement to the increase of energy consumption of a single consumer and the indirect rebound effects of energy efficiency improvement to the increase of the total energy consumption. Based on equations (2) and (12), we have the rebound effects about energy consumption as follows.

Proposition 3. *The improvement of energy efficiency has both direct and indirect effects. The direct rebound effects increase energy consumption by* $\tilde{\varepsilon}-\varepsilon$, *while the indirect rebound effects increase energy consumption by* $\frac{K(\tilde{\varepsilon}+\varepsilon-2\tau)(\tilde{\varepsilon}-\varepsilon)(\tilde{\varepsilon}-\tau)}{2(K+1)}$.

Proof. See in Appendix. ■

Increasing energy efficiency stimulates energy consumption of each consumer directly. This is direct rebound effects and direct rebound effects increase with the energy efficiency improvement of zero-cost breakthrough. Moreover, zero-cost breakthrough extends market size and causes indirect rebound effects. This indirect rebound effects also increase with the energy efficiency improvement of zero-cost breakthrough. Moreover, by $\frac{NK[2u_0+\varepsilon^2-3\varepsilon\tau+3\tau^2+(\varepsilon-3\tau)\tilde{\varepsilon}+\tilde{\varepsilon}^2-2c](\tilde{\varepsilon}-\varepsilon)}{2(K+1)u_0}$, we conclude that competition increases the indirect rebound effects.

For this energy-depended industry, energy efficiency improvement of zero-cost breakthrough improves energy consumption for each consumer and we calculate direct rebound effects. The results of Proposition 3 show that energy efficiency improvement increases consumer surplus but may not reduce energy consumption. For the whole industry, zero-cost breakthrough improves the market share and the indirect rebound effects are achieved. We further address the rebound effects on environment.

We also consider both the emission of each consumer and the total emission. By direct calculation, we have the following conclusions.

Proposition 4. (*a*) *For each consumer, the corresponding emission change is* $(\tilde{\varepsilon}-\varepsilon)[1+\tau-(\tilde{\varepsilon}+\varepsilon)]$. *For the whole industry, the total emission change is given as follows*:

$\frac{NK}{u_0(K+1)}\left\{\left[u_0+\frac{1}{2}(\tilde{\varepsilon}-\tau)^2-c\right](\tilde{\varepsilon}-\tau)^2(1-\tilde{\varepsilon})-\left[u_0+\frac{1}{2}(\varepsilon-\tau)^2-c\right](\varepsilon-\tau)^2(1-\varepsilon)\right\}$; *(b) direct rebound effect of energy efficiency improvement decreases the emission for each consumer if* $\tilde{\varepsilon}>1+\tau-\varepsilon$, *while it increases the emission if* $\tilde{\varepsilon}<1+\tau-\varepsilon$.

Proof. All the results of Proposition 4 can be obtained by direct calculation and we ignore it here. ∎

Although zero-cost breakthrough increases energy consumption for each consumer, the emission for each consumer may decrease under certain condition. For the total emission, we have the similar conclusion. Moreover, by virtue of the total emission change, we know that the competition of each consumer has amplified effects on the total emission change.

The results of Proposition 4 show that the increase of total consumers will enhance the rebound effects of energy efficiency improvement, which can be seen as competitive effects. Therefore, the corresponding policy implication is to launch entry regulation to reduce competition. By restriction of entry, both the total energy consumption and the total emission are reduced for energy conservation and reducing emission. In practice, many regions and countries of the world practice strict entry policies to reduce energy consumption. For example, the government of Singapore restricts the number of automobile cars and some large cities in China, such as Beijing, Shanghai and Guangzhou also have the similar policy.

5.2. Price jump of energy

Price fluctuation usually happens in energy industry and it has crucial influence on energy consumption. In the above analysis, we neglect the price change of energy. In short term, the energy is stable and the above conclusions are rational. But in the long run, energy price jumps, so we will discuss it in details. Assume that energy price after energy efficiency promotion to be $\tilde{\tau}$, where $\tilde{\tau}>\tau>0$. Each (possible) consumer's energy demand is

$$e^{*,3}=\tilde{\varepsilon}-\tilde{\tau}. \tag{17}$$

The emission of each consumer is

$$EM^{*,3}=(1-\tilde{\varepsilon})(\tilde{\varepsilon}-\tilde{\tau}). \tag{18}$$

Denote $\widehat{A}=u_0+\frac{1}{2}(\tilde{\varepsilon}-\tilde{\tau})^2>0$ and $\widehat{B}=\frac{u_0}{N(\tilde{\varepsilon}-\tilde{\tau})}$. The total demand is $\widehat{Q}=\frac{K(\widehat{A}-c)}{\widehat{B}(K+1)}$. The corresponding price is

$$p^{*,3}=\frac{\widehat{A}+Kc}{K+1}. \tag{19}$$

The total energy demand is

$$Q_e^{*3}=N\left(1-\theta^{*3}\right)e^{*3}=N\left[1-\frac{p^{*3}-\frac{1}{2}(\tilde{\varepsilon}-\tilde{\tau})^2}{u_0}\right](\tilde{\varepsilon}-\tilde{\tau}).$$

The corresponding total emission becomes

$$TEM^{*,3}=N\left[\frac{Ku_0-Kc+\frac{K}{2}(\tilde{\varepsilon}-\tilde{\tau})^2}{u_0(K+1)}\right](\tilde{\varepsilon}-\tilde{\tau})(1-\tilde{\varepsilon}). \tag{20}$$

Based on equations 17–20 and compared with equations 12–16, we achieve the following conclusions.

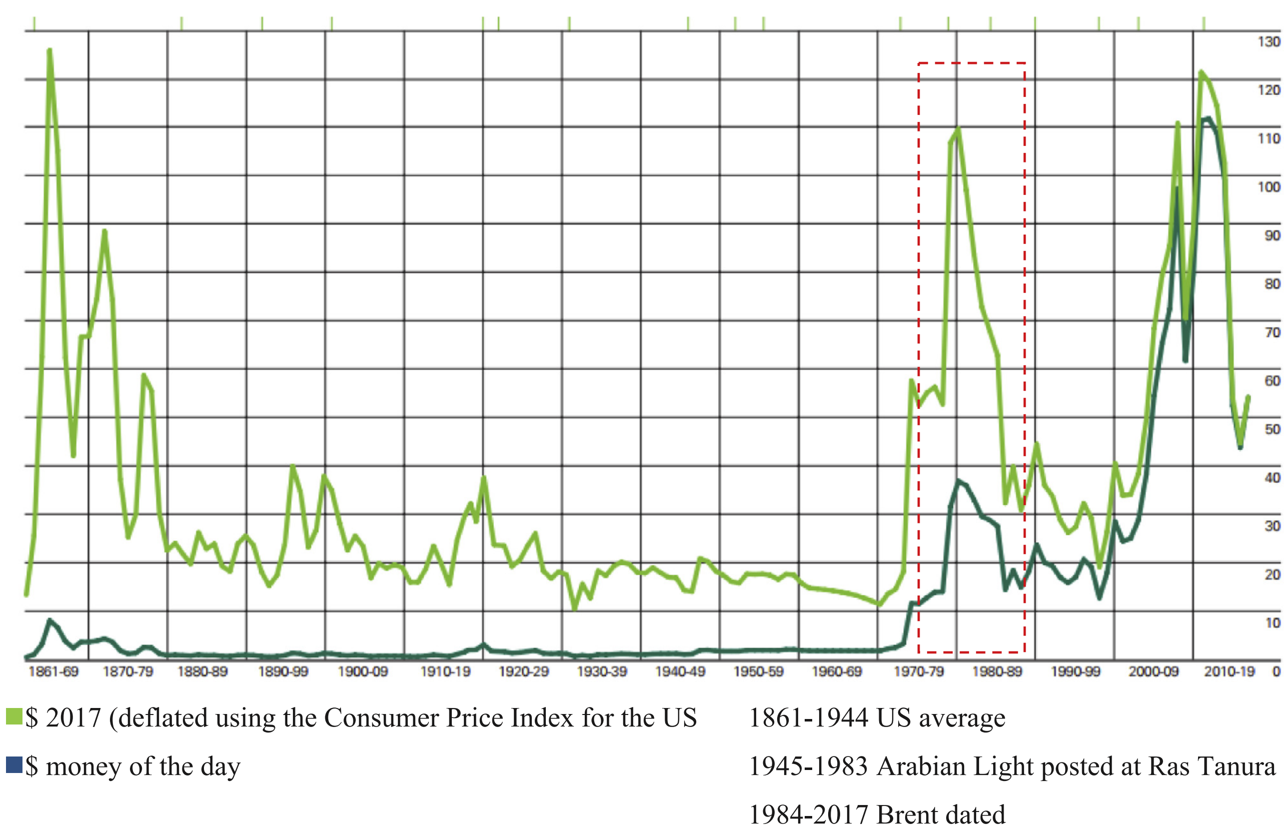

Fig. 1. Crude oil prices 1861–2017. Notes: The data of Fig. 1 are from BP Statistical Review of World Energy : (https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy/oil/oil-prices.html).

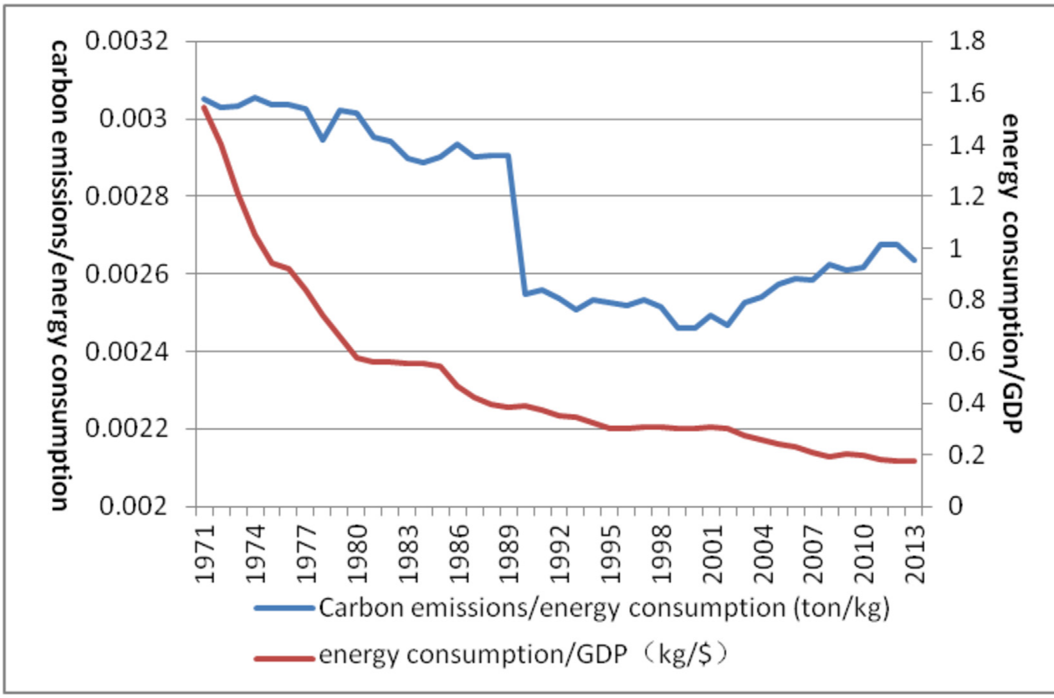

Fig. 2. Energy efficiency and Carbon emissions 1971–2013. Notes: (a) The data of Fig. 2 are from The World Bank. (b) We define energy efficiency as per GDP energy consumption, and the lower per GDP energy consumption, the higher energy efficiency is. (c) Because of the increase of global GDP, both energy consumption and carbon emission are increasing. Considering these facts, we adjust carbon emissions with total energy consumption. (d) For missing of the data before 1970s, we just use the data after 1970s.

Proposition 5. *Under zero-cost breakthrough, energy price jump reduces outputs and price of the final products. Furthermore, the total emission of this industry is also reduced.*

With zero-cost breakthrough, both direct rebound effects and indirect rebound effects are weakened because jumping of energy price plays opposite roles compared with energy efficiency promotion. Therefore, the above conclusions hold. Those results are consistent with the reality. There are three obvious jumping for world crude oil price. For example, before 1970s, energy price kept stable and energy efficiency promotion increases energy consumption and emission to a great degree. But after 1970s, energy price jumped sharply and the rebound effects of energy efficiency on emission are weakened (See Figs. 1 and 2).

Fig. 1 shows that Crude oil price was stable from 1870 to 1970. But it jumped up sharply after 1970s and then goes down quickly in 1980. In Fig. 2, per GDP energy consumption represents energy efficiency, and the lower per GDP energy consumption, the higher energy efficiency is. As the global GDP increasing, both energy consumption and carbon emission are increasing, so we adjust carbon emissions with total energy consumption. From Fig. 2, we learn that adjusted carbon emission is decreasing as the increase of energy efficiency promotion. Moreover, combining Figs. 1 and 2, we can find that price jump of energy reduces the carbon emission in 1970–2010.

6. Concluding remarks

This article investigates the rebound effects of energy efficiency improvement from zero-cost breakthrough. Both the direct and indirect rebound effects are captured in details. On one hand, energy efficiency improvement stimulates energy consumption, while it may reduce total emission. On the other hand, under fixed energy price or no price fluctuation condition, competition amplifies the rebound effects energy efficiency improvement. To keep a sustainable development, the corresponding policy implication is to restrict entries to relieve the competition.

The paper arms to illustrate the rebound effects of energy efficiency improvement on energy consumption. Moreover, we capture the influence of competition and price fluctuation on rebound effects by employing a multiple-oligopoly Cournot competition model, which will distinguish the novel theoretical contribution of our study from other papers. Meanwhile, we propose that the regulators should take rebound effects of energy efficiency improvement and competition condition into consideration when they plan to enforce energy efficiency promotion policies in practice.

The limitations of this study are outlined as follows. First, energy consumption in production sector is ignored. Second, we follow the symmetric assumption about firms in this paper. Third, governmental strategies are exogenous decided. So some further researching topics arise. First, it is interesting to consider the energy consumption both in final product production and consumption progresses. Besides, we assume all firms are identical, but it is interesting to extend asymmetric situation. When firms' position is introduced, firms' strategies will differ and it is important to be discussed. Furthermore, governmental strategies have vertical influence to energy consumption. All these topics are our further research.

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Appendix

Proof of Proposition 1. According to $Q = \frac{K(A-c)}{B(K+1)}$ and $A = u_0 + \frac{1}{2}(\varepsilon-\tau)^2 > 0$, we have

$$\frac{\partial Q}{\partial \varepsilon} = \frac{KN}{(K+1)u_0}\left[(\varepsilon-\tau)^2 + u_0 + \frac{1}{2}(\varepsilon-\tau)^2 - c\right] > 0$$

and $\frac{\partial Q}{\partial \tau} = -\frac{KN}{(K+1)u_0}\left[(\varepsilon-\tau)^2 + u_0 + \frac{1}{2}(\varepsilon-\tau)^2 - c\right] < 0$.

For the price, we have $\frac{\partial p^{*1}}{\partial \varepsilon} = \frac{1}{K+1}\frac{\partial A}{\partial \varepsilon} = \frac{1}{K+1}(\varepsilon-\tau) > 0$and $\frac{\partial p^{*1}}{\partial \tau} = \frac{1}{K+1}\frac{\partial A}{\partial \tau} = -\frac{1}{K+1}(\varepsilon-\tau) < 0$. Thus, improving energy efficiency (or reducing energy price) advances both the total supply and the price.

Moreover, $Q = \frac{K(A-c)}{B(K+1)} = \frac{1}{B}\left[(A-c) - \frac{(A-c)}{K+1}\right]$ and the total outputs increase with the number of firms. From equation (9), we know that $p^{*1} = A - \frac{K(A-c)}{K+1} = \frac{A+Kc}{K+1} = c + \frac{A-c}{K+1}$ and the price decreases with the number of firms. Therefore, competition promotes the outputs but reduces the price.

Conclusions are achieved and the Proof is complete. ▮

Proof of Proposition 2. Combining equations (9) and (11), we have the expression of total emission in equilibrium follow:

$$TEM^{*1} = N\left[1 - \frac{p^{*1} - \frac{1}{2}(\varepsilon-\tau)^2}{u_0}\right](\varepsilon-\tau)(1-\varepsilon).$$

Then we achieve the following results:

$\frac{\partial TEM^{*1}}{\partial p^{*1}} = -\frac{N(\varepsilon-\tau)(1-\varepsilon)}{u_0} < 0$and $\frac{\partial TEM^{*1}}{\partial N} = \left[1 - \frac{p^{*1} - \frac{1}{2}(\varepsilon-\tau)^2}{u_0}\right](\varepsilon-\tau)(1-\varepsilon) > 0$.

Conclusions are achieved and the Proof is complete. ▮

Proof of Proposition 3. Obviously, from functions (2) and (12), the rebound effects of each consumer on energy consumption (direct rebound effects) increase energy consumption by $\tilde{\varepsilon} - \varepsilon$.

Here we consider indirect rebound effects. The total energy consumption increased by as follows

$$Q_e^{*2} - Q_e^{*1} = \frac{NK\left[2u_0 + \varepsilon^2 - 3\varepsilon\tau + 3\tau^2 + (\varepsilon - 3\tau)\tilde{\varepsilon} + \tilde{\varepsilon}^2 - 2c\right](\tilde{\varepsilon} - \varepsilon)}{2(K+1)u_0}.$$

Therefore, conclusions are achieved and the Proof is complete. ▮

References

Berkhout, P.H., Muskens, J.C., Velthuijsen, J.W., 2000. Defining the rebound effect. Energy Pol. 28 (6), 425–432.
Chen, Y.H., Nie, P.Y., Wang, X.H., 2015. Asymmetric duopoly competition with innovation spillover and input constraints. J. Bus. Econ. Manag. 16 (6), 1124–1139.
Chen, Y.H., He, Q.Y., Paudel, K.P., 2018a. Quality competition and reputation of restaurants: the effects of capacity constraints. Economic Research-Ekonomska Istraživanja 31 (1), 102–118.
Chen, Y.H., Wen, X.W., Wang, B., Nie, P.Y., 2017. Agricultural pollution and regulation: how to subsidize agriculture? J. Clean. Prod. 164, 258–264.
Chen, Z.Y., Nie, P.Y., 2016. Effects of carbon tax on social welfare: a case study of China. Appl. Energy 183, 1607–1615.
Chen, Z.Y., Huang, Z.H., Nie, P.Y., 2018b. Industrial characteristics and consumption efficiency from a nexus perspective–Based on Anhui's Empirical Statistics. Energy Pol. 115, 281–290.
Fan, R., Luo, M., Zhang, P., 2016. A study on evolution of energy intensity in China with heterogeneity and rebound effect. Energy 99, 159–169.
Freire-Gonzalez, J., 2017a. A new way to estimate the direct and indirect rebound effect and other rebound indicators. Energy 128, 394–402.
Freire-Gonzalez, J., 2017b. Evidence of direct and indirect rebound effect in households in EU-27 countries. Energy Pol. 102, 270–276.
Fujimi, T., Kajitani, Y., Chang, S.E., 2016. Effective and persistent changes in household energy-saving behaviors: evidence from post-tsunami Japan. Appl. Energy 167, 93–106.
Galvin, R., Sunikka-Blank, M., 2016. Quantification of (p) rebound effects in retrofit policies–Why does it matter? Energy 95, 415–424.
Galvin, R., 2016. Rebound effects from speed and acceleration in electric and internal combustion engine cars: an empirical and conceptual investigation. Appl. Energy 172, 207–216.
Georges, E., Cornélusse, B., Ernst, D., Lemort, V., Mathieu, S., 2017. Residential heat pump as flexible load for direct control service with parametrized duration and rebound effect. Appl. Energy 187, 140–153.
Gillingham, K., Rapson, D., Wagner, G., 2016. The rebound effect and energy efficiency policy. Rev. Environ. Econ. Pol. 10 (1), 68–88.
Gillingham, K., Jenn, A., Azevedo, I.M., 2015. Heterogeneity in the response to gasoline prices: evidence from Pennsylvania and implications for the rebound effect. Energy Econ. 52, S41–S52.
Gillingham, K., Kotchen, M.J., Rapson, D.S., Wagner, G., 2013. Energy policy: the rebound effect is overplayed. Nature 493 (7433), 475–476.
Hache, E., Leboullenger, D., Mignon, V., 2017. Beyond average energy consumption in the French residential housing market: a household classification approach. Energy Pol. 107, 82–95.
Hymel, K.M., Small, K.A., 2015. The rebound effect for automobile travel: asymmetric response to price changes and novel features of the 2000s. Energy Econ. 49, 93–103.
Jiang, M.X., Yang, D.X., Chen, Z.Y., Nie, P.Y., 2016. Market power in auction and efficiency in emission permits allocation. J. Environ. Manag. 183, 576–583.
Li, J., Lin, B., 2017. Rebound effect by incorporating endogenous energy efficiency: a comparison between heavy industry and light industry. Appl. Energy 200, 347–357.
Li, H., Bao, Q., Ren, X., Xie, Y., Ren, J., Yang, Y., 2017. Reducing rebound effect through fossil subsidies reform: a comprehensive evaluation in China. J. Clean. Prod. 141, 305–314.
Lin, B., Tian, R., 2017. Estimating energy conservation potential in China's energy intensive industries with rebound effect. J. Clean. Prod. 156, 899–901.
Llorca, M., Jamasb, T., 2017. Energy efficiency and rebound effect in European road freight transport. Transport. Res. Part A 101, 98–110.
Min, J., Azevedo, I.L., Hakkarainen, P., 2015. Assessing regional differences in lighting heat replacement effects in residential buildings across the United States. Appl. Energy 141, 12–18.
Nie, P.Y., Yang, Y.C., 2016. Effects of energy price fluctuations on industries with energy inputs: an application to China. Appl. Energy 165, 329–334.
Nie, P.Y., Yang, Y.C., Chen, Y.H., Wang, Z.H., 2016a. How to subsidize energy efficiency under duopoly efficiently? Appl. Energy 175, 31–39.
Nie, P.Y., Chen, Y.H., Yang, Y.C., Wang, X.H., 2016b. Subsidies in carbon finance for promoting renewable energy development. J. Clean. Prod. 139, 677–684.
Nie, P.Y., Chen, Y.H., 2012. Duopoly competitions with capacity constrained input. Econ. Modell. 29 (5), 1715–1721.
Nie, P.Y., Wang, C., Yang, Y.C., 2017. Comparison of energy efficiency subsidies under market power. Energy Pol. 110, 144–149.
Nie, P.Y., Wang, C., Chen, Z.Y., Chen, Y.H., 2018a. A theoretic analysis of key person insurance. Economic Modelling 71, 272–278.
Nie, P.Y., Wang, C., Chen, Y.H., Yang, Y.C., 2018b. Effects of switching costs on innovative investment. Technol. Econ. Dev. Econ. 24 (3), 933–949.
Nie, P.Y., Wang, C., Chen, Y.H., 2018c. Top runner program in China: a theoretical analysis for potential subsidies. Energy Strategy Reviews 21, 157–162.
Norero, J.G., Sauma, E.E., 2012. Ex-ante assessment of the implementation of an energy efficiency certificate scheme in Chile. J. Energy Eng. 138 (2), 63–72.
Orea, L., Llorca, M., Filippini, M., 2015. A new approach to measuring the rebound effect associated to energy efficiency improvements: an application to the US residential energy demand. Energy Econ. 49, 599–609.
Sacco, D., Schmutzler, A., 2011. Is there a U-shaped relation between competition and investment? Int. J. Ind. Organ. 29, 65–73.
Sun, P., Nie, P.Y., 2015. A comparative study of feed-in tariff and renewable portfolio standard policy in renewable energy industry. Renew. Energy 74, 255–262.
Wang, C., Nie, P.Y., Peng, D.H., Li, Z.H., 2017. Green insurance subsidy for promoting clean production innovation. J. Clean. Prod. 148, 111–117.
Wang, Z., Han, B., Lu, M., 2016. Measurement of energy rebound effect in households: evidence from residential electricity consumption in Beijing, China. Renew. Sustain. Energy Rev. 58, 852–861.
Watts, R.J., Howsawkeng, J., Teel, A.L., 2005. Destruction of a carbon tetrachloride dense nonaqueous phase liquid by modified Fenton's reagent. J. Environ. Eng. 131 (7), 1114–1119.
Yang, D.X., Nie, P.Y., 2016a. Influence of optimal government subsidies for renewable energy enterprises. IET Renew. Power Gener. 10 (9), 1413–1421.
Yang, D.X., Chen, Z.Y., Nie, P.Y., 2016. Output subsidy of renewable energy power industry under asymmetric information. Energy 117, 291–299.
Yang, Y.C., Nie, P.Y., 2016. Asymmetric competition in food industry with product substitutability. Agric. Econ.–Czech 62, 324–333.
Zhang, Y.J., Peng, H.R., 2017. Exploring the direct rebound effect of residential electricity consumption: an empirical study in China. Appl. Energy 196, 132–141.